measured to be less than 3 meters per second. The low values of wind reinforced the conclusion that the cloud was a condensate. Consequently, it was believed that this feature would not interfere with either the lander entry or postlanding imaging. The successful landing occurred on 20 July 1976 at 5:12 a.m. PDT.

The lander pictures showed abundant blocks consistent with the presence of small impact craters in the vicinity. It is therefore suggested that the high radar reflectivity indicates that bedrock is near the surface and many blocks can be ejected by the impact. Such areas should be carefully considered prior to acceptance as landing sites in the future. Further discussion of both the visual and radar characteristics is presented by Carr *et al.* (*2*) and Tyler *et al.* (*3*), respectively.

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4. The Viking Site Certification effort represented the combined efforts of nearly the entire Viking flight team. Some of those involved in the almost daily activities of the landing site staff include: M. J. Alazard, D. L. Anderson, W. A. Baum, K. Blemann, J. Boyce, G. A. Briggs, D. B. Campbell, M. H. Carr, H. Craft, J. A. Cutts, D. M. Davies, G. S. Downs, F. Drake, V. R. Eshleman, C. B. Farmer, W. Farrell, E. A. Flinn, J. Gliozzi, R. M. Goldstein, J. D. Goodlette, R. Greeley, R. R. Green, J. E. Guest, R. Hargraves, S. L. Hess, N. Hinners, W. Jakobowski, H. H. Kieffer, L. Kingsland, K. P. Klassen, H. P. Klein, R. S. Kraemer, C. Leovy, P. T. Lyman, T. Z. Martin, H. Masursky, W. H. Michael, H. J. Moore, II, E. C. Morris, T. A. Mutch, J. F. Newcomb, F. T. Nicholson, W. J. O'Neil, T. Owen, F. D. Palluconi, J. D. Porter, R. J. Reichert, C. Sagan, G. Schaber, R. A. Simpson, R. W. Sjostrom, B. A. Smith, C. W. Snyder, L. Soderblom, G. A. Soffen, T. E. Thorpe, P. Toulmin, III, G. L. Tyler, E. D. Vogt, plus several hundred or so others at JPL and the U.S. Geological Survey at Flagstaff, Arizona, who also supplied brains and hands to make the system work. J. S. Martin, Jr., A. T. Young, and B. G. Lee were the recipients of the recommendations of the landing site staff and patiently endured our long march northwest across Chryse Planitia.

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Radar Characteristics of Viking 1 Landing Sites

Abstract. *Radar observations of Mars at centimeter wavelengths in May, June, and July 1976 provided estimates of surface roughness and reflectivity in three potential landing areas for Viking 1. Surface roughness is characterized by the distribution of surface landing slopes or tilts on lateral scales of the order of 1 to 10 meters; measurements of surface reflectivity are indicators of bulk surface density in the uppermost few centimeters. By these measures, the Viking 1 landing site at 47.5°W, 22.4°N is rougher than the martian average, although it may be near the martian average for elevations accessible to Viking, and is estimated to be near the Mars average in reflectivity. The A1NW site at the center of Chryse Planitia, 43.5°W, 23.4°N, may be an area of anomalous radar characteristics, indicative of extreme, small-scale roughness, very low surface density, or a combination of these two characteristics. Low signal-to-noise ratio observations of the original Chryse site at 34°W, 19.5°N indicate that that area is at least twice as rough as the Mars average.*

The surface properties of Mars determined by Earth-based radar were one of several factors that were considered in selecting the Viking 1 lander site. Estimates were made of surface roughness and density based on spectral broadening and the strength of centimeter-wavelength radio echoes returned from Mars.

Radar observations have been conducted at each Mars opposition since 1963. Since 1968 a combination of geometrical constraints and system sensitivity limitations have restricted these measurements to Mars latitudes south of 15°N, that is, below the planned landing areas of both the first and second Viking missions. Recent improvements at both Arecibo Observatory (*1*) and Goldstone Tracking Station (*2*) made observations feasible at 20°N in May and June 1976 and at 23°N from Arecibo in July. At these times the planet's distance was about 2 A.U. as compared with about 0.5 A.U. at opposition. The wavelengths of observation were 3.5 cm and 12.6 cm at the Goldstone and Arecibo facilities, respectively. Observational conditions and site locations are summarized in Table 1.

The use of radar in site selection for Viking 1 was based on properties of radiowave scatter in the immediate vicinity of the sub-Earth point on Mars. Near that point, radiowave scatter is dominated by the multitude of reflections from those portions of the surface that are properly oriented to produce a mirrorlike, or near-specular, redirection of the incident energy back toward Earth. This component of the scatter is dubbed quasi-specular. For surfaces that are generally free of sharp discontinuities and are of homogeneous material and statistics, it can be shown that quasi-specular scatter is controlled by the combination of the surface slope distribution and the electromagnetic properties of the material (*3*). Under these conditions the effects of surface material and roughness are readily separated with the use of standard radar astronomy techniques (*4*). Methods used here, based on backscatter at normal incidence, should not be confused with earlier radar studies of lunar landing sites that were based on backscatter observed at oblique angles of incidence, especially the depolarized part of diffuse scatter (*5*).

Both observatories transmitted unmodulated signals. Echoes of these signals were broadened in frequency by the Doppler effect and the differing relative velocities of various scattering areas with respect to the radar. The broadening associated with quasi-specular scatter is quantitatively related to the distribution of surface slopes. A gauge of surface roughness was obtained from measurements of the one-half power bandwidth of the echo signals. The results were expressed in terms of an r.m.s. landing slope β_0. Comparative values of β_0 for lunar units are given in Table 2. The methods employed have been previously tested by comparing radar results from the moon with detailed analyses of the lunar surface at the same locations based on orbital photogrammetry (*6*).

Reflectivity corresponds to the Fresnel reflection coefficient of the mean surface material, or $\rho_0 = [(\sqrt{\epsilon} - 1)/(\sqrt{\epsilon} + 1)]^2$, where ϵ is the dielectric constant. The relationship between density of the surface and ϵ has been established from laboratory experiments and theory (*7*). The lateral scale of relevant slopes is of the order of from 1 to 10 m based on theoretical considerations and on empirical results from the moon (*8*); estimates of ρ_0 apply to the top few centimeters of the surface.

Values of β_0 depend primarily on the shape of the echo spectrum, and are generally free of systematic error. Estimates quoted below are typically accurate to about 10 percent. Estimates of ρ_0 depend on a number of multiplicative parameters which are obtained by calibration of the radar. In addition, ρ_0 is sensitive to variations in the radar, such as antenna pointing errors, during a period of observation. At Arecibo such pointing errors are probably the dominant error source and may occasionally be as large as a factor of about 2. At Goldstone, the error due to system calibration and pointing is estimated to be no greater than about 15 percent, but noise contributes about twice this amount. Most operational errors result in systematic underestimates of ρ_0.

The resolution varied with surface roughness, but was at most approximately the size of the Viking 1 landing ellipse, typically a circle about 300 km in diameter centered at the sub-Earth point. This resolution element moved across the surface as Mars rotated. It was also possible to infer changes in smaller areas within this larger resolution element from the detailed shapes of the echo spectra; however, no reliable quantitative information on surface properties could be obtained for these smaller areas.

Results for A1 and A1R (19.5°N, 34°W and 19.5°N, 32.5°W). Data from these sites consist of two Arecibo passes across the 30° to 35°W longitude range between 17.1° and 17.5°N latitude, and a total of six observations over this longitude range between 17.5° and 19.6°N by the Goldstone facility. The Arecibo observations did not cover the A1 sites directly, but were influenced by terrain at the extreme southwestern end of the A1 and A1R landing ellipses. It was not possible to distinguish between the A1 and A1R areas.

The Arecibo measures of r.m.s. slope show the area just south of A1 to be one of moderate to large roughness. Values of β_0 range from a minimum of $\beta_0 \simeq 5°$ to 6° to the southwest of the site, to an estimated lower bound of $\beta_0 \gtrsim 7°$ to the southeast. The most probable value of surface reflectivity from Arecibo is $\rho_0 \simeq 0.07$, albeit this value is subject to large systematic errors. Goldstone observations on 2 days at latitudes between about 17.2° and 17.6°N yielded results consistent with those from Arecibo, $\beta_0 \simeq 6.4°$, $\rho_0 \simeq 0.08$; but the signal-to-noise ratio was low, on the order of 5 : 1. Echoes from each of four individual Goldstone observations at latitudes of 18.2°, 18.4°, 18.6°, and 19.7°N in the range of 33° to 35°W longitude were very near the detection threshold. However, echoes from other locations on Mars, especially the A2 site (see below), were readily observed at Goldstone during this same time period. Extensive system testing revealed no equipment faults. Combining all Goldstone observations at the six latitudes above yielded an apparently reliable echo detection at the A1 site and gave values of β_0 between 7° and 10°, and $\rho_0 \simeq 0.06$.

Both the Arecibo and Goldstone results indicated that the area just south of the A1 sites is approximately twice as rough as the average for Mars. The estimated reflectivity is near Mars' average. In terms of lunar results, with the same measures, this area would be characterized as similar to very rough lunar mare,

Table 1. Radar observations of Viking 1 sites.

Location	Date in 1976	One-way light time	Observational Latitude	Observational Longitude
	The A1 site from Arecibo Observatory at 12.6 cm			
19.5°N, 34°W	29 May	16.1 min	17.1°N	30° to 36°W
	31 May	16.1 min	17.5°N	30° to 36°W
	The A1 site from Goldstone Observatory at 3.5 cm			
19.5°N, 32.5°W	29 May		17.1° to 19.6°N	
	30 May		17.1° to 19.6°N	
	31 May		17.1° to 19.6°N	
	1 June		17.1° to 19.6°N	
	3 June		17.1° to 19.6°N	
	11 June		17.1° to 19.6°N	
	The A1NW site from Arecibo Observatory at 12.6 cm			
23.4°N, 43.4°W	3 July	18.2 min	23.1°N	38° to 49°W
	4 July	18.2 min	23.3°N	38° to 49°W
	The A1WNW Viking 1 landing site from Arecibo Observatory at 12.6 cm			
22.4°N, 47.5°W	3 July	18.2 min	23.1°N	38° to 49°W
	4 July	18.2 min	23.3°N	38° to 49°W
	The A2 site from Arecibo Observatory at 12.6 cm			
19.5°N, 252°W	12 June	17.0 min	19.6° to 20°N	248° to 254°W
	14 June	17.0 min	19.6° to 20°N	248° to 254°W
	The A2 site from Goldstone Observatory at 3.5 cm			
	11 June			
	13 June			
	14 June			

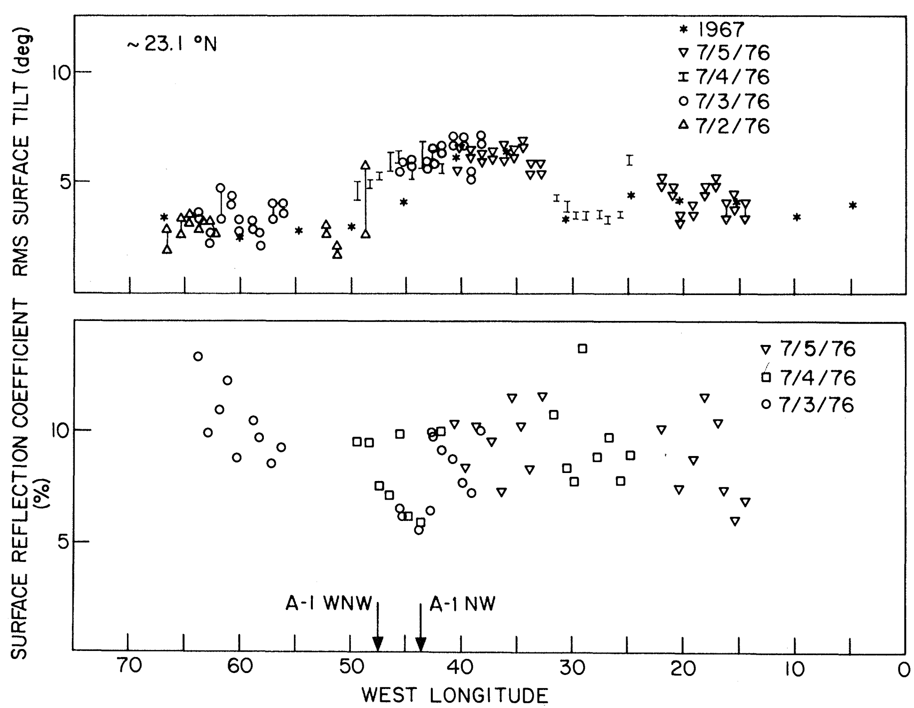

Fig. 1. Estimated values of r.m.s. landing slope and surface reflectivity at approximately 23°N latitude. Observations reported here are from 2, 3, 4, and 5 July 1976, averaged over 0.7° in longitude. Points from Carpenter (stars) are from data integrated over about 10° in longitude, at 22.5°N latitude (9). No values of reflectivity from Carpenter have been used. Data show Chryse Planitia to be generally rougher than areas to the east or west. The Viking 1 landing site at 47.5°W lies in a region of changing radar roughness. Site at 44.5°W is in a region of anomalous radar signature. Values of r.m.s. slope and reflectivity at 47.5°W correspond to average lunar mare in roughness and Mars average density, respectively.

or smooth uplands, while the average surface density would be greater.

The difficulties experienced by the Goldstone facility in obtaining reliable echo detection in the immediate vicinity of the A1 and A1R sites while echoes were obtained from the area just to the south and from elsewhere indicate that at best the surface properties are no better than, or more likely are somewhat degraded with respect to, the 17.5°N latitude in terms of the desirable characteristics for landing safety.

A radar scatter simulation program was used to demonstrate the effect of surface roughness on signal detectability and to determine approximate bounds on the characteristics of the surface in the A1 area. It was shown that echoes from the A1 and A1R sites would have been observed by Goldstone each day if those sites contained an area 3° in diameter with the same radar characteristics as the A2 site.

Results for A2 (19.5°N, 252°W). Both Arecibo and Goldstone facilities obtained data from the area of the A2 ellipse. The observations yielded consistent results for r.m.s. slopes of $\beta_0 \simeq 3.5°$ to 4°. Values of ρ_0 from Arecibo varied between about 0.03 and 0.07, with an average value of 0.05; the estimate from Goldstone is $\rho_0 \simeq 0.06$. These values indicate a surface near Mars' average or slightly greater in roughness, and near lunar average, or slightly less than Mars' average, in surface reflectivity.

Results for A1NW and A1WNW (23.4°N, 43.4°W and 22.4°N, 47.5°W). Observations of the A1NW and A1WNW sites were carried out by the Arecibo Observatory during the same period that the Viking 1 orbiter was conducting its photographic reconnaissance of that area. Successful observations of 40° to 50°W longitude at about 23.2°N were obtained on 2 days, with overlapping coverage in the 42° to 46°W longitude range. Additional observations were obtained about 20° to both the east and the west of the A1NW and A1WNW area, but with only partial coverage.

The Chryse Planitia basin appears to the radar to be generally rougher than the areas to either the east or the west. This result is consistent with earlier observations by Carpenter (*9*) at the same wavelength at 22.5°N latitude (see Fig. 1). The principal difference between the current results and those from 1967 is in signal-to-noise ratio. In 1967 it was necessary to average over 10° of martian longitude to obtain useful results. The current observations, even though at greater range, require only about 0.7° of averaging to obtain signal-to-noise ratios in excess of 10 : 1.

Table 2. Comparative values of β_0 for lunar units.

Lunar unit	β_0*
Rough uplands	9° to 10°
Smooth uplands	7°
Rough mare	5.5° to 6.5°
Average mare	4.5° to 5.5°
Smooth mare	4.5°
Average Mars	3.5°

*From 13 cm radar.

On the average, the Chryse Planitia basin is slightly smoother than the area to the south of the original A1 site, with r.m.s. slopes and reflectivities of $\beta_0 \simeq 5°$ to 6° and $\rho_0 \simeq 0.07$ to 0.08, respectively. However, the roughness data, from both the current observations and those of Carpenter, show a decline in surface roughness west of about 45°W longitude, with further decreases in roughness east and west of about 35° and 50°W, respectively. At 47°W, the formal values obtained for r.m.s. slope vary over the final landing ellipse between about $\beta_0 \simeq 4.5°$ 5.5°, with reflectivity of $\rho_0 \sim 0.07$ or greater. If correct, this value of ρ_0 implies a surface density near 2 g/cm^3. At 44°W, the formal value of r.m.s. slope is $\beta_0 \simeq 6°$. There is an anomalous decrease in the apparent reflectivity in the vicinity of 44°W. Although this change was observed on two successive days (see Fig. 1), there is a question as to its reliability because of general difficulties in steering the Arecibo antenna.

The variable nature of the area around 44°W is also apparent in the shape of the echo spectra. Data from 3 and 4 July show the same effects. Spectra adjacent to those from 44°W are systematically skewed with respect to their usual, symmetrical shape. The sense of skew is opposite for sub-Earth points to the east and west. The shape changes smoothly with longitude and is consistent with a limited area of relatively weaker backscatter located near 44°W. Similar progressive changes in spectral shape have been observed in bistatic-radar experiments on the moon where the visible feature associated with the change in radar properties, usually an isolated crater, could be easily identified. Small-scale surface roughness, a very tenuous surface layer, or a combination of these could be used to explain this behavior.

The area of anomalous radar signature in Chryse Planitia coincides with the deepest, most central portions of the basin. This area is also marked by an absence of wind streaks visible in the Viking 1 images to both the east and the west. Other features of the radar data indicate that there might be local areas of relative smoothness on either side of, but principally to the east of, the anomalous area. However, no realistic quantitative results could be obtained from these features.

The radar properties of the A1WNW site appear to be similar to the average results of Chryse Planitia or to indicate a surface slightly smoother than the average of that area. But of more importance, the 47.5°W ellipse does not appear as an area of anomalous radar scatter, although it is in an area of transition. The formal results indicate that the large-scale roughness, excluding blocks, is similar to average lunar mare, while the surface reflectivity is apparently near martian average, or greater than that of the moon.

Comparison with images. Interpretation of Viking 1 orbiter images with an identification resolution near 140 m (*10*) revealed new features in the vicinity of the A1 landing site (19.5°N, 34°W). Initial impressions of the Viking images in the area placed the surface roughness in a category with rough lunar mare or smooth lunar upland. The broad-scale appearance is more akin to a lunar upland, perhaps rougher than indicated by radar track to the south, but consistent with the inferences from Goldstone data in the A1 area. The visual impressions were confirmed by photogrammetry at slope length near 500 m.

Farther to the northwest at the final landing site, the surface judged from the images appeared smoother and consistent with the radar results. That is, the surface is more akin to a lunar mare than a lunar upland. The images indicate that the aeolian processes of deflation, erosion, and deposition have occurred. Small cratering events have excavated material from an underlying dark layer about 50 m thick. These craters were subsequently modified by the wind. Bright windtail deposits were produced on the southwest sides, while their northeast flanks were stripped, exposing dark material. Of equal importance to the physical properties of the martian surface are the ubiquitous impact craters ranging in size from 200 m to several tens of kilometers. Large blocks, fragments, and crushed rock were ejected. Occasional blocks near the limit of resolution, 250 m across, are visible on the rims of craters about 20 km across. Thus, it was clear that the surface was complex with probable exposures of bare rock and the products of impact cratering, such as blocks, fragments, crushed rock, and that the surface has been modified by the wind. Such a surface is expected to yield a larger reflection coefficient than the average lunar surface.

Images from the lander camera reveal the martian surface as relatively smooth. It is characterized by bare rock, blocks, rock fragments, and finer debris with superposed aeolian deposits and wind-deflated or eroded surfaces. These observations are consistent with the orbital images, the radar estimates of roughness, and the relatively large, compared with the moon, values of reflection coefficient obtained.

Conclusions. Radar and imaging form complementary techniques. Images provide information in the form of recognizable patterns which can be interpreted and analyzed quantitatively to provide an estimate of surface state on a lateral scale that is at one to three times the resolution of the imaging system. Inferences from Viking orbital images regarding surface structure on the scale of the lander require extrapolation of surface properties downward over 1½ to 2 orders of magnitude. Radar provides only an average measure of surface properties on the scale of the lander over an area comparable to the size of the landing ellipse. Radar observations detected an area of anomalous small-scale structure and reflectivity at the A1NW site.

The present radar observations are limited by the signal-to-noise ratio and by difficulties in absolute calibration of received power. They cannot be relied upon to detect areas of extreme roughness, such as a limited number of impact craters, which comprise only a small fraction of the resolution cell. The use of radar and images together compensates in part for the individual limitations of two techniques and provides data on all scales of surface roughness greater than about 1 m.

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10. The theoretical resolution element, or pixel, is near 37 m. It takes an array, 3 pixels on a side, to identify a feature such as a crater.
11. We offer our deep appreciation to R. A. Simpson for his efforts in data collection, reduction, and analysis. This work was conducted at Stanford University and at the Jet Propulsion Laboratory under contract with the Viking Project. We thank the staff of the Arecibo Observatory for their cooperation and help, and V. R. Eshleman and R. M. Goldstein for guidance, and N. L. Crabill for much help.

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